Launch Vehicle Propulsion Life Cycle Cost Lessons Learned

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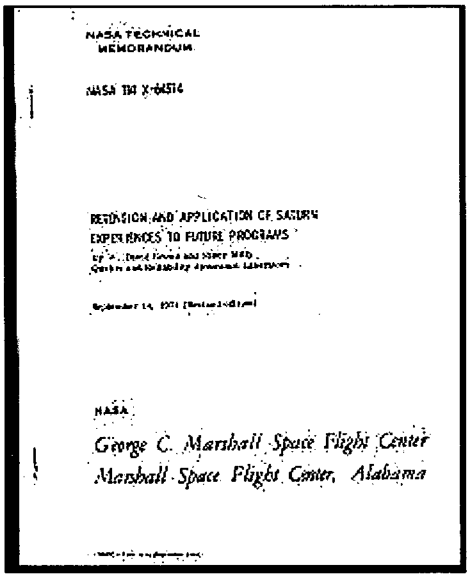
This paper will review lessons learned for space transportation systems from the viewpoint of the NASA, Industry and academia Space Propulsion Synergy Team (SPST). The paper provides the basic idea and history of "lessons learned". Recommendations that are extremely relevant to NASA's future investments in research, program development and operations are provided. Lastly, a novel and useful approach to documenting lessons learned is recommended, so as to most effectively guide future NASA investments. Applying lessons learned can significantly improve access to space for cargo or people by focusing limited funds on the right areas and needs for improvement. Many NASA human space flight initiatives have faltered, been re-directed or been outright canceled since the birth of the Space Shuttle program. The reasons given at the time have been seemingly unique. It will be shown that there are common threads as lessons learned in many a past initiative.

I. Introduction

NASA's space flight programs have had an interest in lessons learned since the start of space flight. In 1971, with the Apollo missions to the Moon nearly over, NASA published the "[1]Retention and Application of Saturn Experiences to Future Programs". This is an example (**Figure 1**) of an early attempt at documenting lessons learned, summarizing and organizing bits of wisdom. This memorandum was a practical guide full of details that might be overlooked by someone new to the field of launch vehicles and infrastructure. Under "Lines and Ducts" was a lesson about "Stainless Steel Ducting", observing that corrosion of welds could be a problem, unless one was to "avoid use of carbon steel wire brushes during fabrication".


NASA TECHNICAL
MEMORANDUM

NASA TM X-64514

RETENTION AND APPLICATION OF SATURN
EXPERIENCES TO FUTURE PROGRAMS

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

Figure 1. The earliest of lessons learned attempts. Compiling the experience of individuals by parts or sub-systems categories.

Leaping ahead to today (**Figure 2**), the internet has replaced the memorandum of yesteryear as a way of gathering up lessons learned using such a "bottoms-up approach". Lessons learned can be submitted or searched for on the internet at the [2]NASA Engineering Network. The term "bottoms-up" is used here, as the lessons are not asked for in the context of any higher levels goals or needs that guide, organize or prioritize the information. The term "top-down" approach will be used to refer to using goals and needs to generate and prioritize lessons learned.

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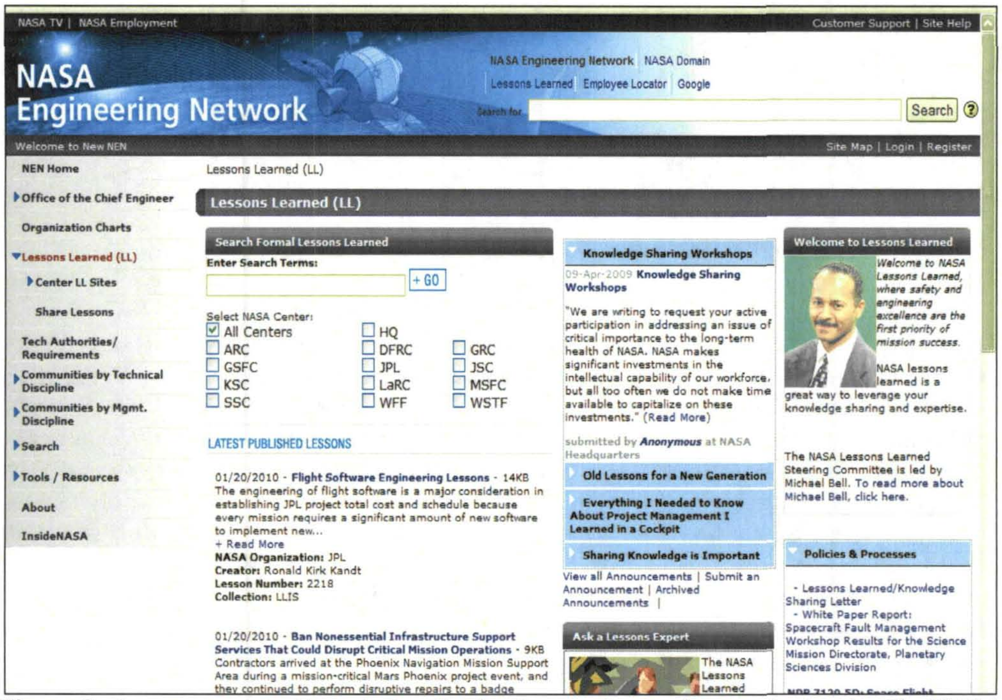

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Figure 2: A more recent attempt at gathering lessons learned, now electronic. The NASA Engineering Network asks users to submit their experience electronically, easeing some search capability.

Not all lessons learned are technical. Werner Von Braun wrote of [3]management practices in the early days of NASA, including recommendations about politics and the relation to budgets, preserving in-house capabilities, organizational sizes, and good communication in project teams. Such lessons can be referred to as "programmatic" lessons in NASA-speak, or as "management" lessons or "business practices" in more general terms.

Realizing that categories can help better communicate lessons learned, as if to say these drivers, causes or factors differ in basic class from all these other ones, these are a different "dial" to affect the outcome, projects may categorize lessons into buckets. The DC-X program categorized its [4]lessons learned by (1) management, (2) technical and (3) operations and supportability. Common threads show that NASA and industry tend to use the word "technical" to talk about how a system was designed or manufactured, as well as operated.

The struggle is to define useful categories and further breakouts of the "technical" vs. "management" lessons, while realizing that even these two broad categories may be inadequate to the entire task. For example, management of an enterprise (more than one large program) or even just one large program across very long time frames, easily creates a third class of lessons learned, [5]strategic lessons, very much apart from the lessons that a sub-project would surface. Similarly, lesson categories for management might also diverge from "leadership" lessons given distinctions there.

If a lesson is to be "[6]knowledge or understanding gained by experience" and if "the experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure" there is no need to be constrained to only a technical list, a detailed observation or a bottoms-up perspective. In reviewing traditional references, lessons learned are seen to be detailed observations about some problem, or success, and a cause that was seemingly causal. The question "why is the sky blue" is too often not asked five times, leading to documenting only immediate causes. An alternative to the bottoms-up collecting of lessons learned is a "top-down" approach, using a process that is "goal" and "need" driven rather than "project" driven. Either approach requires a well-defined structure for categorizing to exploit the knowledge best. This alternate perspective on lessons learned is provided in part as a response to the failure of lessons learned to be learned, and the tendency of most lessons learned documents to largely gather dust on the shelves (or today, in databases) for lack of a larger context and purpose.

II. Background, the Space Propulsion Synergy Team

The current Space Propulsion Synergy Team (SPST) traces it's origins to 1991 and the chartering of a group of NASA, industry, university and aerospace related stakeholders by then NASA Headquarters. The goal was to develop innovative engineering processes that could meet the challenges of the day by enlisting the diverse experience of the team members.

The SPST first emphasized that while access to space for cargo or people had numerous management and technical challenges, from development, through design and manufacture, all the way to launch site processing and in-space operations, the real need to improve lie elsewhere. The greatest need identified for improvement was not in reaching LEO, it was in making future access to space more affordable, safer, reliable, widespread and routine.

Getting to space was already possible. The semi-reusable Shuttle, and many other expendable launch systems, US or foreign, could all get to Low Earth Orbit (LEO) and beyond. Decades of investment had established robust data, infrastructure, and workforces leading to wholly new industries and markets worth [7]hundreds of billions of dollars a year. Humans had been to the Moon and back, and in-space operations stretched out to the edge of the solar system. The Global satellite infrastructure today provides for images of our Earth and its weather, for communications, television, radio and global positioning. Given enough time, money and the right organization to accomplish the task, access to space was not an impossible problem. It was an engineering and scientific challenge to repeat and enhance. This difference between a challenge and what needed to be focused on for improvement would become clearer as the SPST began its work focused on organizing improvement "needs" across categories of "-ilities", those items so many lessons try to relate to such as reliability, affordability and so on. This distinction between getting to space and improving access to space is best contrasted when considering research and development (R&D), early design decisions in new programs, and technology demonstrations using existing systems vs. on-going business.

- The "-ilities"
    - Affordability
    - Reliability / Safety
    - Maintainability
    - Supportability
    - Operability
    - Flight Rate Capability

Eventually numerous discrete pieces of work by the SPST would be accomplished along the previous lines of investigation. The SPST continues as an ad-hoc organization bringing together senior, experienced personnel from NASA, industry and academia to consider, define and communicate what are essentially lessons learned from a top-down, goals and needs driven perspective. When considering the multi-faceted question of how to one day achieve routine, affordable, reliable (and safe) access to space a host of other questions become clearer that lend understanding and wisdom useful for setting direction.

The discrete tasks that have been undertaken by the SPST, with relevance to lessons learned, include:

A. Structured Prioritization Process for Decision Making Support

Organizing when communicating useful experience is crucial to avoiding the syndrome of creating endless hit lists, a dictionary, or a database of detailed to-do's within contexts that are so specific to time and place as to be overwhelming or useless. Among the first tasks chartered to the SPST was a technology prioritization process. However, in order to achieve such a prioritized technology listing devoid of a specific architecture it was first necessary to re-think the process of "prioritizing".

The result was a structured systematic process:

Step 1: Identify the attributes of a space transportation system; system meaning flight and ground elements, with attributes varying depending on if the system was in the R&D phase, the acquisition phase, etc.

Step 2: Prioritize the attributes, using a score based on the importance, the need to improve, and the improvement required relative to the current state of the art.

Step 3: Prioritize measurable criteria, using cross-correlation to the prioritized attributes. In this way tangible drivers or the lessons to take forward, could be ordered to surface the most important, actionable items that would affect the attributes. The "few" would be separated from the "many" (aka Pareto principle). This process, also know as a Quality Functional Deployment or "QFD" is essentially about connecting the "why", "what" and "how" in going about improvements, as shown notionally in **Figure 3**.

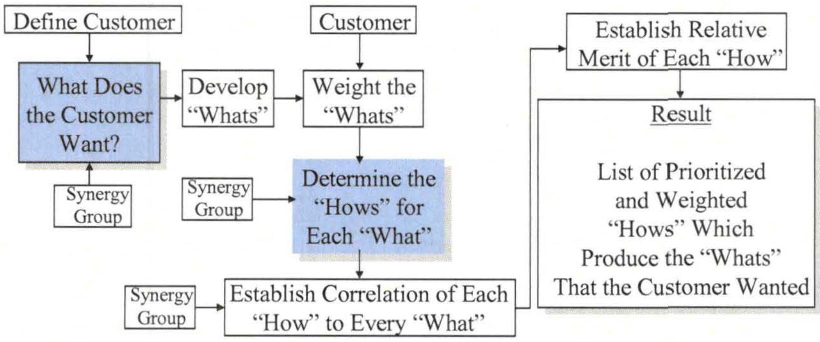


Figure 3: A Notional description of a technology prioritization process. This assists in connecting why all the way to how.

A first lesson in all this, applicable to any improvement, initiative or investment decision was to be clear on "why". Determining "why" for the early SPST centered on finding the lessons that would improve the "-ilities" of future space transportation systems. It was a given to the team members that "the [8]success of expanded human presence and commercial activity in space hinges on the affordability of future space transportation".

A first lesson learned then, in attempting to gather, document and communicate experience, was to clearly understand why, what and how, and to prioritize the experience using structured, semi-quantifiable methods. Brainstorming has its place, as does any bottoms-up process of collecting inputs from subject matter experts, but within a broader picture of limited resources it is important to be structured in the decision-making steps prior to making investments.

Among the lessons surfaced as priorities applicable to space transportation design and acquisition were:

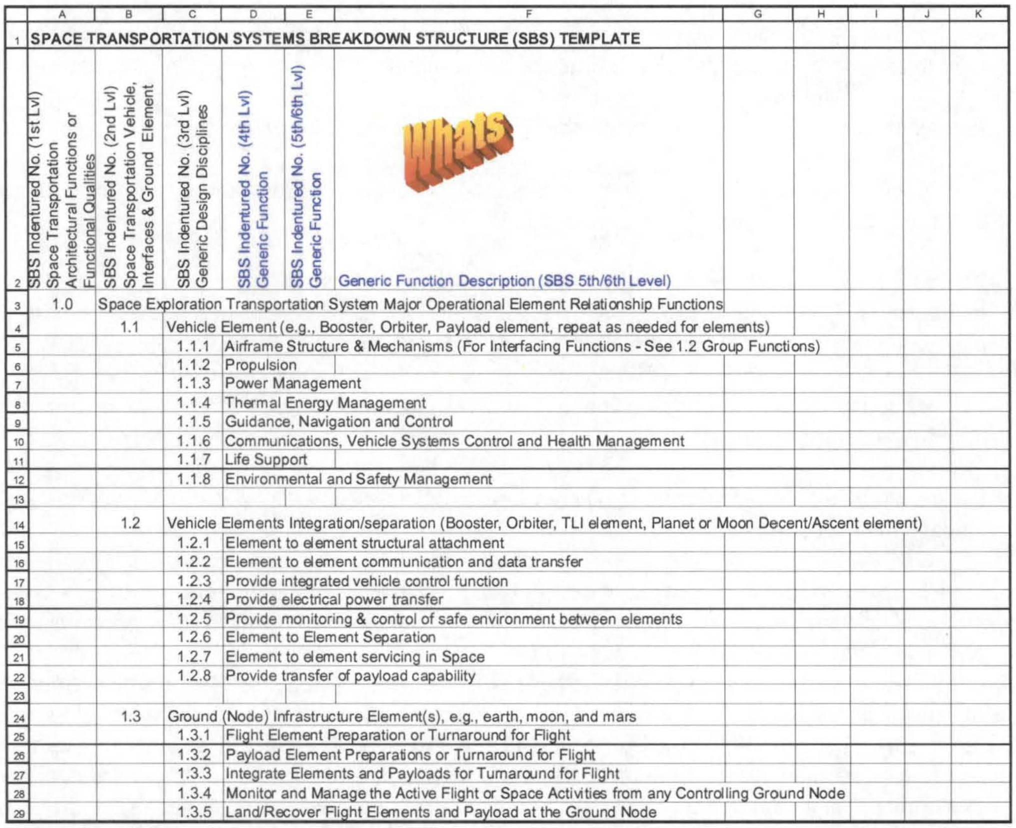
1. Reduce the number of toxic fluids
2. Increase system margin
3. Increase the built in test capabilities of systems
4. Reduce the number of confined, and/or purged spaces
5. Reduce the number of different propulsion systems and engines
6. Reduce the number of unique stages
7. Reduce the active ground systems required
8. Reduce the number of purges
9. Reduce the number of potential leakage / connection / interface sites
10. Reduce the number of active systems to keep a safe system
11. Reduce the number of different fluids

Notably, many of these are specific versions of more recent themes like "commonality" in design or "simplicity", but in a much more useful, focused format, stemming from a process that has surfaced a quantifiable driver, based on a goal. Fluids can be counted in existing systems. They can be counted in proposed system designs. Are there 25% fewer different fluids in a proposed design vs. an existing baseline (assuming similar capability)? The simpler vehicle will make significant headway on both up-front and later recurring costs. This is a tangible, clear driver, avoiding vagueness, making clear if a design is the same as what has come before vs. better. Later SPST documents would explain each of these measurable criteria in the form of a [9]guide, equivalent to lessons learned focused on significant improvement around affordability and other "-ilities". The ability to take all such criteria for a whole "score" of any concept, architecture, or technology A vs. B or C would also be a crucial outcome linked to being a semi-quantifiable process (without which the structure of all this knowledge would lose significant usefulness). This process lends itself to an objective function being developed that is useful, usable and has been used.

B. Functional Analysis

Follow-on work by the SPST took the question of "how" further, organizing knowledge about a system functionally. Traditionally, NASA and its contractors use the work breakdown structure or "WBS" lists the purpose being to divide and conquer. Unfortunately, this approach is frequently related to "Weight Breakdown Structures" at detailed levels as the item to be built, acquired, or operated has sub-systems such as propulsion, thermal protection systems, a fuel cell, etc where "work" and "weight" organize in parallel to each other. Ultimately even organizational charts assign personnel according to similar if not identical areas that breakout the parts of a launch vehicle and its ground systems infrastructure. All of these breakdown structures are attempts to decompose a thing into smaller and smaller pieces on the theory that smaller pieces are more easily understood, managed, built and operated. The idea is to reduce interactions to manageable levels, increasing specialization, with ulterior motives such as quality control. Modern manufacturing concepts are versions of this breakdown of a process step by step to make an item part by part. The downside of such decomposition becomes encouraging complexity by reducing the capacity of the process to identify (1) duplication of parts or processes and (2) innovative opportunities among parts and processes to join up, become a single module, or otherwise improve capability while reducing cost.

In contrast, the SPST innovation about "how" a launch vehicle and its infrastructure carries out it's functions was to avoid jumping too quickly into design solutions before further understanding those functions. Common functions can then be addressed with greater integration in a design, thereby addressing measurable criteria of the sort outlined previously. [10]Extensive tables were developed along these lines as shown in **Figure 4**.



	A	B	C	D	E	F	G	H	I	J	K
1	SPACE TRANSPORTATION SYSTEMS BREAKDOWN STRUCTURE (SBS) TEMPLATE										
2	SBS Indentured No. (1st Lvl) Space Transportation Architectural Functions or Functional Qualities	SBS Indentured No. (2nd Lvl) Space Transportation Vehicle, Interfaces & Ground Element	SBS Indentured No. (3rd Lvl) Generic Design Disciplines	SBS Indentured No. (4th Lvl) Generic Function	SBS Indentured No. (5th/6th Lvl) Generic Function	Whats Generic Function Description (SBS 5th/6th Level)					
3	1.0	Space Exploration Transportation System Major Operational Element Relationship Functions									
4		1.1	Vehicle Element (e.g., Booster, Orbiter, Payload element, repeat as needed for elements)								
5			1.1.1	Airframe Structure & Mechanisms (For Interfacing Functions - See 1.2 Group Functions)							
6			1.1.2	Propulsion							
7			1.1.3	Power Management							
8			1.1.4	Thermal Energy Management							
9			1.1.5	Guidance, Navigation and Control							
10			1.1.6	Communications, Vehicle Systems Control and Health Management							
11			1.1.7	Life Support							
12			1.1.8	Environmental and Safety Management							
13											
14		1.2	Vehicle Elements Integration/separation (Booster, Orbiter, TLI element, Planet or Moon Decent/Ascent element)								
15			1.2.1	Element to element structural attachment							
16			1.2.2	Element to element communication and data transfer							
17			1.2.3	Provide integrated vehicle control function							
18			1.2.4	Provide electrical power transfer							
19			1.2.5	Provide monitoring & control of safe environment between elements							
20			1.2.6	Element to Element Separation							
21			1.2.7	Element to element servicing in Space							
22			1.2.8	Provide transfer of payload capability							
23											
24		1.3	Ground (Node) Infrastructure Element(s), e.g., earth, moon, and mars								
25			1.3.1	Flight Element Preparation or Turnaround for Flight							
26			1.3.2	Payload Element Preparations or Turnaround for Flight							
27			1.3.3	Integrate Elements and Payloads for Tumaround for Flight							
28			1.3.4	Monitor and Manage the Active Flight or Space Activities from any Controlling Ground Node							
29			1.3.5	Land/Recover Flight Elements and Payload at the Ground Node							

Figure 4: A functional breakdown structure for organizing design work. Rather than use weight or the work to make a product, the task to be accomplished by the product is used as the focus.

To see this more clearly by way of example, an Orbital Maneuvering System and a Reaction Control System are both sub-systems by which work can be assigned, in which buckets of allocated weight can be tracked (engines, plumbing, gases, electronics, actuators, etc) and for which people are assigned responsibilities. Functionally if the two sub-systems are called "in-space propulsion" the chance arises from taking this different perspective to join up the hardware from each system to the common task ("in-space propulsion"), resulting in less hardware. Tanks may be common, the same and fewer tanks feeding both engines and thrusters.

In summary, a "functional" view is one where opportunities for both improvement and real integration (at the shared hardware level) can be both derived and better addressed. This is in contrast to the traditional approach that tears systems apart to a degree that integration really becomes just the remaining coordination among sub-systems that have been disconnected from each other to the maximum extent possible. The traditional attempt at reducing sub-systems interactions actually increases overall complexity as measured by parts count proliferation, with all its attendant ill effects. The functional view offers another innovative departure point for defining more affordable, reliable, routine access to space.

C. Life Cycle Cost Control Lessons

Having stressed affordability since its inception, the SPST most recently delved into the topic of life cycle cost control methods. SPST member experience surfaced the analogy of controlling costs in a manner similar to the way weight or performance is treated in launch vehicle programs. Design to life cycle cost should be a rigorous process. The foundation must be implemented and demonstrated during the early part of the vehicle design program. It is a process where trades-offs among development, operational, performance, schedule, risk, DDT&E costs, and life cycle costs must be addressed on a continuing basis. An ability to control costs within stringent total program and fiscal constraints must be demonstrated early in the design development phase and must be carried through until the last day of operation of the vehicles developed under the program.

Key features of a Design to Life Cycle Cost Management process would include:

1. Cost credibility through the use of extensive cost databases to develop initial values and operation cost models to assure the credibility of initial, early estimates.

2. Assessing annual funding constraints strategically; exploring alternative system concepts.

3. Use of a Design to Life Cycle Cost Management manager reporting directly to the program manager, providing a high level, single point of contact.

4. A Design to Life Cycle Cost Management process which is an integral part of a performance management system; assuring an integrated cost management system that is coupled with the technical performance measurement system to enhance the early detection of unfavorable trends.

5. Cost effective design solutions through system engineering control of the technical performance and operation cost assessments;

6. Early establishment of realistic, yet rigorously defined cost objectives within highly visible management processes and discipline.

There should be a focus on both development and operational cost containment. If system cost projections exceed target values, design trades should be initiated to redefine system design characteristics to a level that supports system costs requirements. This makes most of the previous ingredients un-like current cost control processes. None of these steps should be confused here with alternate systems such as Earned Value Management (EVM), use of confidence levels in cost estimating, Pert diagrams, scheduling tools, or other tools that have their place. The difference in this proposed Life-Cycle-Cost-Control methodology lies in emphasizing a future recurring operations cost projection, inclusive of productive flight rate or a similar metric, to guide current decisions and costs in design, development, test and engineering. Without such a view systems developments are condemned to emphasize near term costs to "get there", the non-recurring capital expense day-to-day or any year, only to field systems that fail to make any advancement toward more routine, affordable, safer, access to space.

III. Recent Events

Many SPST members, as is the case with this generation of NASA, industry and academia, have had the opportunity to participate in NASA programs beyond Apollo, Shuttle, or the International Space Station. NASA has had a host of programs since it began advertising the need to move beyond the Space Shuttle. The National Aerospace Plane or "NASP" program was one of the earliest initiatives, in the [11]early 80's, once the Shuttle was flying, in regards to answering what comes next, what follows the semi-reusable Space Shuttle. Unfortunately, the NASP program would be the first of many initiatives in NASA to address the question "what next"? **Figure 5** is testament to an assortment of NASA initiatives, all of which at one point or another sought out lessons learned, and all of which failed to become defined (to date) as what was to build on these past lessons and lead into the future.

At the other end of the spectrum, with the Shuttle program scheduled to have two more flights as of this writing, NASA is in the midst of a re-direction that includes plans to cancel the last initiative at answering the same question – "what next"? The Constellation program has been [12,13]canceled in recent policy setting the NASA Fiscal year 2011 budget.

Prior to this shift in direction, since the more formal start of the Constellation program in 2006, a program defined by two Shuttle derived launch vehicles, there have been numerous analysis that have employed lessons learned in analyzing, modeling and assessment processes. One such process is the NASA Standing Review Board (SRB) process that has emphasized both independent cost estimation of the quantitative sort as well as assessment of the more qualitative sort. Here, lessons such as those previously presented here were incorporated into the analysis of the recurring operations of the Kennedy Space Center Ground Operations Project (GOP).

Using a model, the Launch and Landing Effects Ground Operations (LLEGO) model, lessons that are technical and operational, and very similar to those previously highlighted here, have been turned into quantitative cost estimating relationships (CERs). At it's most sophisticated level (that is currently an enhancement in work through 2010), a model that has turned lessons into CERs can be used to address confidence not just in a proposed budget, but also in the targeted launch rate that represents the reason for the entire project, the productivity. **Figure 6** represents actual output from such a model and is an "existence proof" that lessons learned, well organized and linked to outcomes that too often are left as results or goals, can be used in program processes (such as boards, independent reviews, etc) in quantifiable and credible ways.

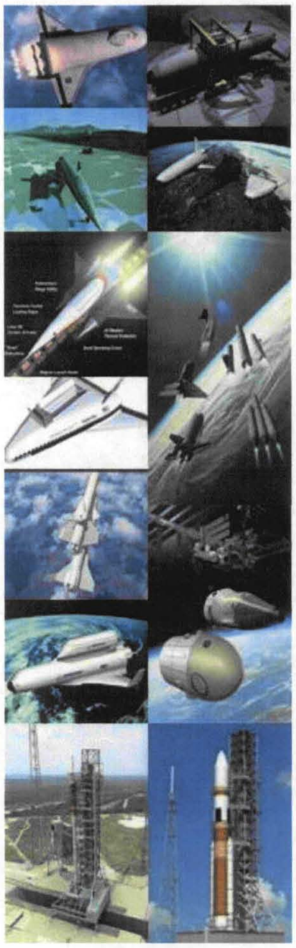
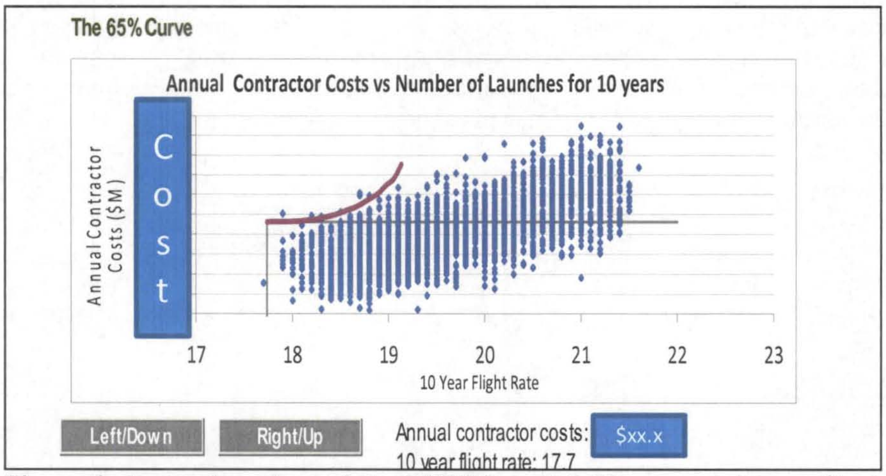


Figure 5: NASA false starts. A handful of representations of what would come after the Space Shuttle.

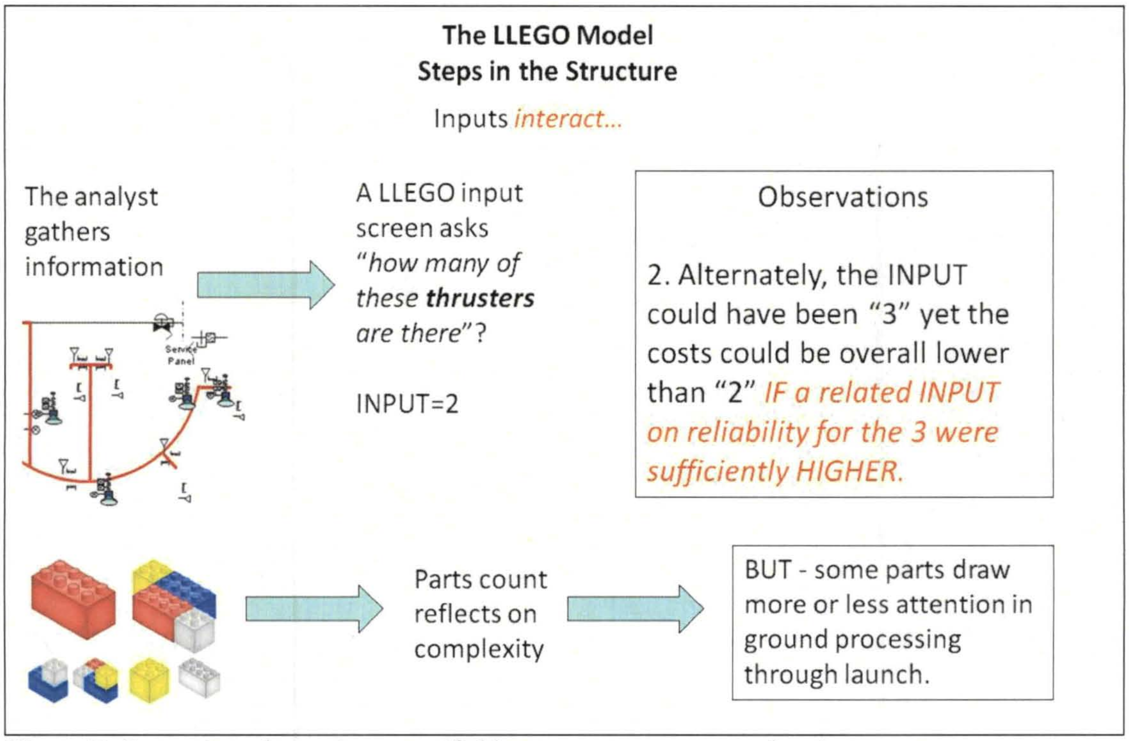


Annual contractor costs: $xx.x

10 year flight rate: 17.7

Figure 6: A sample output of the LLEGO model. Here uncertainty applies in the cost estimated by the model AND in the flight rate productivity.

The LLEGO model uses lessons that are technical (about complexity, reliability, and operability/maintainability), and when applicable any operations and supply chain practices (default to traditional "as is" ways of doing business, or as wholly different ways of doing business), to rack, stack and interact parts of the launch system design. The connection from lessons learned about complexity for example (previously stated as "1. Reduce the number of toxic fluids, 2. Increase system margin, 3. Increase the built in test capabilities of systems, 4. Reduce the number of confined, and/or purged spaces, etc) to dollars, and thus affordability and flight rate, is shown very notionally in **Figure 7**.



The LLEGO Model
Steps in the Structure

Inputs *interact...*

The analyst gathers information

A LLEGO input screen asks *"how many of these* ***thrusters*** *are there"*?

INPUT=2

Observations

2. Alternately, the INPUT could have been "3" yet the costs could be overall lower than "2" *IF a related INPUT on reliability for the 3 were sufficiently HIGHER.*

Parts count reflects on complexity

BUT - some parts draw more or less attention in ground processing through launch.

Figure 7: Converting a lesson into quantifiable support to programs and projects.

IV. Lessons and Technology Development

Beyond qualitative lessons, beyond models, no matter how quantifiable, lie further study, technology development and demonstration. The literature provides ample evidence that lessons learned about reducing complexity, increasing reliability, and making more operable and maintainable systems is possible and is not always at odds with performance concerns of propulsion thrust, Isp, or vehicle dry weight.

Figure 8 shows hardware from an actual prototype seeking to create [14]simplified (reduced parts count, welds, interfaces) turbomachinery for cryogenic rocket application.

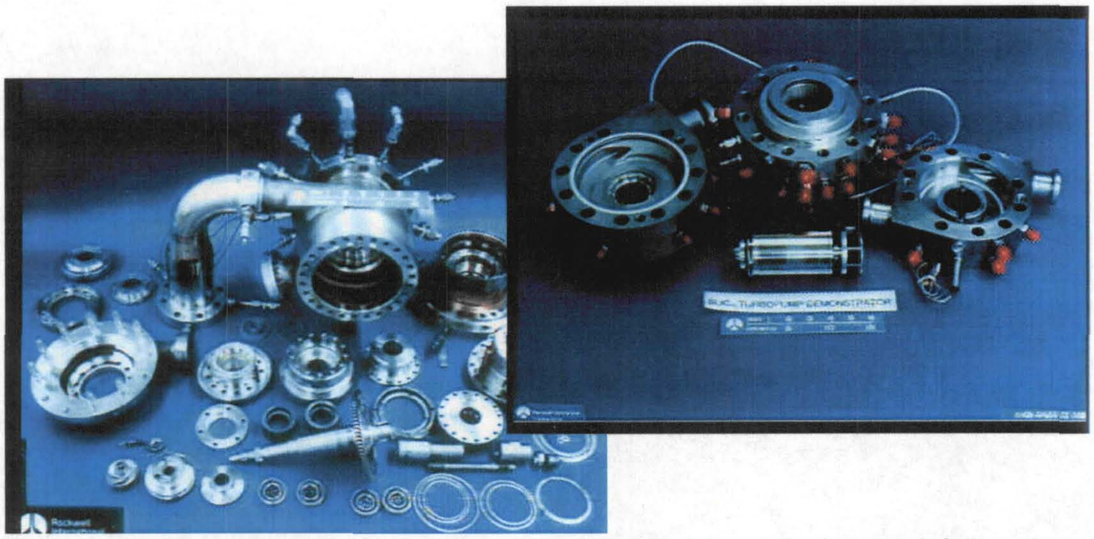


Figure 8: Turbomachinery & lessons learned about parts count: A Turbopump left, in use, as an example of current technology, and a Turbopump right, as a prototype consisting of just four pieces. The proittotype was called the SLIC or "Simple Low-cost Innovative Concept" by Rocketdyne. The SLIC turbopump reached speeds of 77,500 rpm, or about twice the Shuttle's turbopumps. Rather than use ball bearings, the SLIC pump also explored hydrostaic bearing technology (again, fewer parts).

Examples abound of how a lesson in rocket propulsion is to simplify, reducing parts count, having a more modular design, reducing welds and interfaces. Albeit, while technology may inevitably get increasingly more complex as it gets more capable, as more is demanded of it, historical analogies for most high performing technology would indicate that it's possible to simultaneously achieve a greater ease of operation. The importance of increasing reliability is not lost in lessons learned, keeping the ill effects of complexity from overwhelming the objectives – affordability, and more routine, productive system operations.

Along similar lines, **Figure 9** from the US Air Force [15]Integrated Modular Engine study is just one example of taking lessons learned to the next level of stsudy and design formulation. Such work is merely one example of where performance have been shown not to be at odds with lessons learned. The challenges associated with such system designs are about focusing the organization on the right "-ilities".

By way of further example, lessons such as reduced parts count have been implemented when designing even advanced liquid hydrogen turbopumps, the most challenging of applications. **Figure 10** shows work from 1999 developing and testing an advanced liquid hydrogen turbopump where [16]"low parts count simplifies assembly". Once again it can be obssrved that some lessons have surfaced to the top of the list. It remains a task for the propulsion community to develop and undersatand the entire list and to apply these lessons in further test and demonstration leading to operational, commercial systems.

Lastly, reliability and operability can not be emphasized enough. If capability is to increase in propulsion, and the entire launch system (flight & ground), it is inevitable that reliability and operability lessons must be further adopted in systems design. Reliability issues are repeatedly surfaced in lessons learned exercises, stressing early design "test-fail-fix" cycles to deliver a product that is ready for operations. Reliability and reusability inevitably go hand-in-hand.

Table 1. IME Requirements

Propellants	O_2/H_2
Thrust (lbf)	30,000
Specific Impulse (sec)	>470
Reliability	0.995
Operability	High
Production and development costs	Low

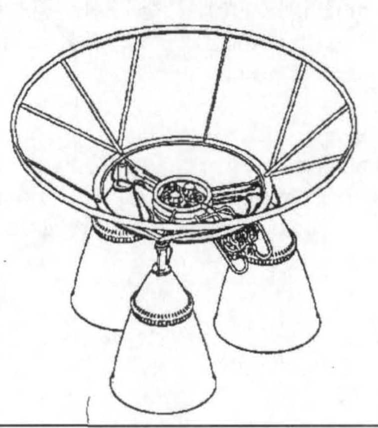


Figure 9: Sharing turbomachinery. From the US Air Force Integrated Modular Engine Study, 1992.

Figure 10: Turbomachinery simplicity: Above for a simplified liquid hydrogen turbpump design, taking to heart the lesson "reduce parts count", vs. below, a current design.

V. Issues for the Industry

There are numerous issues for propulsion as an industry that have not been covered here under the topic of lessons learned. Policy issues include regulations (International Traffic in Arms, "ITAR" rules, etc), as well as competitive issues in contracting relating to spreading knowledge. Where research and development pursues a lesson learned, and this has been R&D fostered by a government agency, such information must also spread much as lessons learned are shared.

VI. Conclusion

Concluding, lessons learned in propulsion and launch systems abound. Teams such as the SPST have been instrumental in making sense of the abundance of lessons from individuals, studies, and organizations. Structure has been shown to be possible when thinking about lessons learned and turning them into useful knowledge. It has been shown that a leap to quantitative models that fundamentally rely on structured lessons learned have evolved and even made their way into some NASA decision support processes. As well, technology development has oftne run sucessfully with the lessons learned that are surfaced as most important in an attempt to change the fundamental nature of our launch systems. If the desire is to improve the launch systems affordability, reliability (safety) and productivity (flight rate per year), the design focus must seek out lessons learned about making systems easier to operate. Nonetheless, realizing significant barriers remain, it is recommended that:

A. NASA should adopt a structure for lessons learned that cleanly seperates and organizes technical (design, flight, ground), business (leadership, management, programmatic) and strategic (policy, goals, regulation) lessons learned.

B. There remains a wealth of lessons learned in the business realm that are often under-explored and under-appreciated for their effect on the enterprise. Improvements in the entire flow of information and materials that ultimately enable a propulsion/vehicle/ground system design, manufacture and operation are critical to furthering the "-ilities" of affordability, reliability and maintainability. The entire supply chain management from customer requirement to supplier and back is an area ripe for lessons learned as expansive and encompassing as efforts to date for the definition of technical lessons learned.

C. There also remains a wealth of lessons learned in the realm of the strategic. Ideas about the competitive structure of industry are under-explored and under-appreciated. Though some work in this area (e.g., the [17]"independent operator" paradigm) has defined a relation between improvements in design and strategic, competitive factors, there is ample work here still to do to surface the right lessons, categorise these and eventually take them to as mature a level as technical lessons.

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